

UTILIZATION OF RECENTLY DEVELOPED CODES FOR HIGH POWER BRAYTON AND RANKINE CYCLE POWER SYSTEMS

Michael P. Doherty
National Aeronautics and Space Administration
Lewis Research Center
Nuclear Propulsion Office
Cleveland, OH 44135

SUMMARY

This paper will present two recently developed FORTRAN computer codes for high power Brayton and Rankine thermodynamic cycle analysis for space power applications. The codes were written in support of an effort to develop a series of subsystem models for multimegawatt Nuclear Electric Propulsion, but their use is not limited just to nuclear heat sources or to electric propulsion.

The paper will provide code development background, a description of the codes, some sample input/output from one of the codes, and state future plans/implications for the use of these codes by NASA's Lewis Research Center.

BACKGROUND

Nuclear Electric Propulsion (NEP) is a propellant-efficient type of low thrust-to-weight propulsion for space-based propulsion applications. NEP systems employ a nuclear reactor as a thermal source in a closed heat transport system to generate electricity, which drives an electric thruster. The electric thruster uses the electrical energy to accelerate a propellant, producing mechanical energy or thrust.

Because low thrust is characteristic of electric propulsion, electric propulsion (EP) only realizes its usefulness in microgravity fields. Near planetary bodies, an EP spacecraft's flight is characterized by a spiral trajectory about the planet until escape is achieved. Once free of the planetary gravity well, the spacecraft's trajectory is as direct as need be for target body intercept. Extremely high EP spacecraft velocities are achieved by continual thrusting over a period of time.

Recent studies have shown NEP to be beneficial for robotic planetary

science, as well as Mars piloted and cargo, missions, offering significant advantages over chemical propulsion, including: reduced vehicle initial mass, reduced transit time, wider launch windows, and planetary rendezvous capability (refs. 1 to 4).

Five major subsystems make up an NEP system: a nuclear reactor (with radiation shield), a power conversion subsystem (or heat engine), a waste heat rejection subsystem, a power management and distribution subsystem, and the electric propulsion subsystem (see Figure 1).

Lewis Research Center's (LeRC) Nuclear Propulsion Office (NPO) and Advanced Space Analysis Office (ASAO) have developed subsystem models to improve LeRC's capability to model NEP systems and predict their performance. Greater depth is needed for NEP system models, to verify performance projections and to assess the impact of specific technology developments. The effort to bring greater depth to system models for NEP was initiated with the development of separate software submodules to model each of the five major subsystems inherent to an NEP system.

Subsystem models were developed by the Oak Ridge National Laboratory (ORNL) for the reactor (ref. 5), by the Rocketdyne Division of Rockwell International for power conversion, heat rejection, and power management and distribution (refs. 6 to 9), and by Sverdrup Technology for the thrusters (ref. 10), with at least two inherently different technology options being modeled for each subsystem.

These models are now resident as VAX/FORTRAN source and executable code on one of LeRC's Scientific VAX computers.

DESCRIPTION OF THE CODES

Rankine cycle heat engines produce useful work by heating a fluid to become a gas, employing the heated gas to do useful work, and condensing the gas back into liquid state. Under this modeling effort, the Rankine cycle power conversion option assumes that a primary liquid metal lithium loop supplies heat from the reactor to the boiler and reheater. This is the basis for the schematic shown in Figure 2, which also depicts the other components that make up this power conversion system. Boiler and reheater are modeled as a once-through design with lithium on the shell side and potassium on the tube side. The turboalternator is modeled as a multistage axial reaction turbine with a two-pole toothless

(permanent magnet) alternator. The condenser is modeled as a shear-controlled flow condenser co-serving as a manifold for a heat pipe radiator. The turbopump is modeled as a single stage centrifugal impeller with inducer, driven by a 45% efficient partial admission turbine. Head losses and piping sizes are also computed.

Brayton cycle heat engines are single-phase working fluid engines which produce useful work by heating a gas under a relatively constant pressure process, employing the heated gas to do useful work, and cooling the gas under another relatively constant pressure process to get it back to its original state. This is the basis for the schematic shown in Figure 3, which also depicts the components making up this power conversion system. This Brayton cycle power conversion model has the capability to model the heat input to the gas as either by direct heating (gas circulated through a reactor) or by indirect heating (gas flowing through a liquid-to-gas heat exchanger). The heat exchanger assumes tube and shell configuration with liquid on the tube side. The Brayton turboalternator-compressor can be modeled as either an axial or radial machine, with a two-pole toothless (permanent magnet) alternator. A ducting algorithm computes the ducting diameter, length, and mass, multifoil insulation mass, and total mass for each ducting segment, as well as providing gas Reynolds number and pressure drop. Finally, the code can analyze both recuperated and non-recuperated system designs.

The codes are applicable for electrical output power ranges of 100-10,000 kilowatts-electric for system lifetimes of 2-10 years, at turbine inlet temperatures ranging from 1200-1600 K (Rankine) and 1200-1500 K (Brayton). The ranges of inlet-to-outlet temperature ratios considered are 1.25-1.6 (Rankine) and 2.5-4.0 (Brayton).

The products or output of these codes include optimal thermodynamic cycle characteristics, component descriptions, dimensions, efficiencies, and operating parameters, and overall subsystem mass. These outputs are provided as clearly dependent upon the input parameters of turbine inlet temperature, temperature ratio, electrical power level, lifetime, materials of design, turbine design, etc.

SAMPLE INPUT/ OUTPUT

To date, the codes have been reasonably well verified (exercised to see that they work), but only have just begun the process of being

validated (determining the reasonableness of their answers). A parametric analysis of a Brayton power system will be presented to demonstrate the potential of the codes.

Using the Brayton code, a set of cases was run to demonstrate the effect of compressor inlet temperature on the overall mass of a specific space nuclear power system design. The significance of this effect should be clarified. Because of the strong impact that mass has on spacecraft performance, spacecraft power systems may not necessarily be designed for maximum efficiency. Rather, the space power system may be design-optimized for minimum mass. This implies that the system design point ultimately chosen may not be one yielding the highest efficiency, but one yielding the lowest mass.

This implication has interesting consequences for the design of a space electric power generation system. Because a power generation system designed for high efficiency requires moderately low heat rejection, and thus "cold-end", statepoint temperatures, its heat rejection will be encumbered by a low fourth-exponent temperature differential, thus requiring large rejection areas (and encumbent high mass) to achieve the required waste heat rejection capacity. On the other hand, for the same output power requirement, if the power generation system is designed with high heat rejection temperatures, the resulting low power conversion efficiency will demand that a large power source (with encumbent mass) be used. Clearly, for an optimized space electric power generation system, the minimum mass point will be associated with a "cold-end" statepoint (usually the compressor inlet for a Brayton power generation system) temperature somewhere in between these extremes. Detailed analytical modeling of the entire power generation system will help determine minimum system mass versus key parameters such as compressor inlet temperature (or temperature ratio).

To demonstrate this point, a 500 kWe Brayton system was analyzed. The system assumed an 1144 K turbine inlet temperature, a radial compressor having a design pressure ratio of 1.8, a radial turbine design, a Helium-Xenon working fluid mixture having a molecular weight of 20, a recuperator efficiency of .85, and an alternator voltage of 1400 V_{rms} . The compressor inlet temperature was varied from 300 K to 500 K (implying a temperature ratio variance from 3.8 to 2.3). For this analysis, the reactor heat source was modeled with the use of the ORNL lithium liquid metal cooled pin type reactor code (ref. 5), while the heat rejection system was

modeled as being a Sodium-Potassium (NaK) pumped loop having a flat plate, water heat pipe radiator in a 1000 km high Earth orbit, by using the Rocketdyne heat rejection code (ref. 8). Statepoint temperatures, pressures, and required heat flows were manually passed from the Brayton code to the reactor and heat rejection codes to achieve system consistency. System specific mass was calculated versus compressor inlet temperature. In this analysis system specific mass is the sum of the reactor mass; Brayton subsystem mass (including turboalternator-compressor, recuperator, ducting, and intermediate heat exchanger); and heat rejection subsystem mass, divided by the electrical power output.] The results of this parametric variation of compressor inlet temperature (CIT) are shown in Figure 4.

As can be seen from the figure, system specific mass is minimized for a CIT of 400 K, a point somewhere in the midst of the examined range. (It is only coincidental that the minimum happens to occur at the midpoint of the chosen range; for the initial conditions of this Brayton design, a CIT design point as low as 250 K is possible, but such a system couldn't operate in Earth orbit. In addition, selection of more data points would have more precisely determined the actual CIT at which the minimum specific mass occurs.) Although the Brayton efficiency at this CIT (24%) is only 73% of the efficiency that could be achieved with a 300 CIT (33%), the mass of its heat rejection system happens to be 33% less. Thus it can be seen that the CIT operating point yielding the minimum system specific mass is not the same point yielding the highest efficiency.

Using the K-Rankine code, a system designer can perform the same kind of trades to determine overall system mass (or specific mass) versus temperature ratio.

UTILIZATION PLANS

A guiding tenet in LeRC's strategic planning for the 1990's is to build upon the strengths of the our Center. At LeRC, our strengths, as evidenced by the roadmap of our history (ref. 11), clearly fall into the disciplines of space power and electric propulsion.

Although these space power and electric propulsion technical areas have had a resurgence in emphasis in recent years - especially so with the potential dawning of major new applications (ref. 12) - there has been a

recent cooling off of intentions to apply these technologies in a major way to new advanced applications. Nevertheless, to indeed build upon the Center's strengths, the Center must maintain a cutting edge in both the technology discipline and systems application of these particular technological areas to the greatest extent possible.

Therefore, these codes, and the system analysis capability they provide, find themselves at the very heart of the future mission of LeRC. Although the Nuclear Propulsion Office will not be formally continued after the end of the fiscal year, the Advanced Space Analysis Office will continue to perform NEP mission and system studies.

Realizing that these studies will be ongoing at LeRC, and recognizing the need for LeRC to maintain a pre-imminence in design, modeling, and analysis of NEP systems for future applications, LeRC is now beginning to implement a new, efficient modeling tool for end-to-end NEP system analysis. This modeling tool will take advantage of an existing generic system modeling, simulation, and analysis environment tool called General Purpose Simulator (or GPS), authored and maintained by the Department of Energy's Argonne National Laboratory (ref. 13). The tool will provide for quick, detailed prototyping of NEP systems that are made up of the subsystem models introduced in this paper (refs. 5 to 10). Such a tool should reduce the analysis time required to create a data curve such as in Figure 4, from as much as 1/2 hour (of analyst's time) per datapoint to mere seconds (the time it takes for a UNIX workstation to respond to the touch of a single keystroke). Before the end of FY93, this system modeling capability is planned to be implemented to some initial degree.

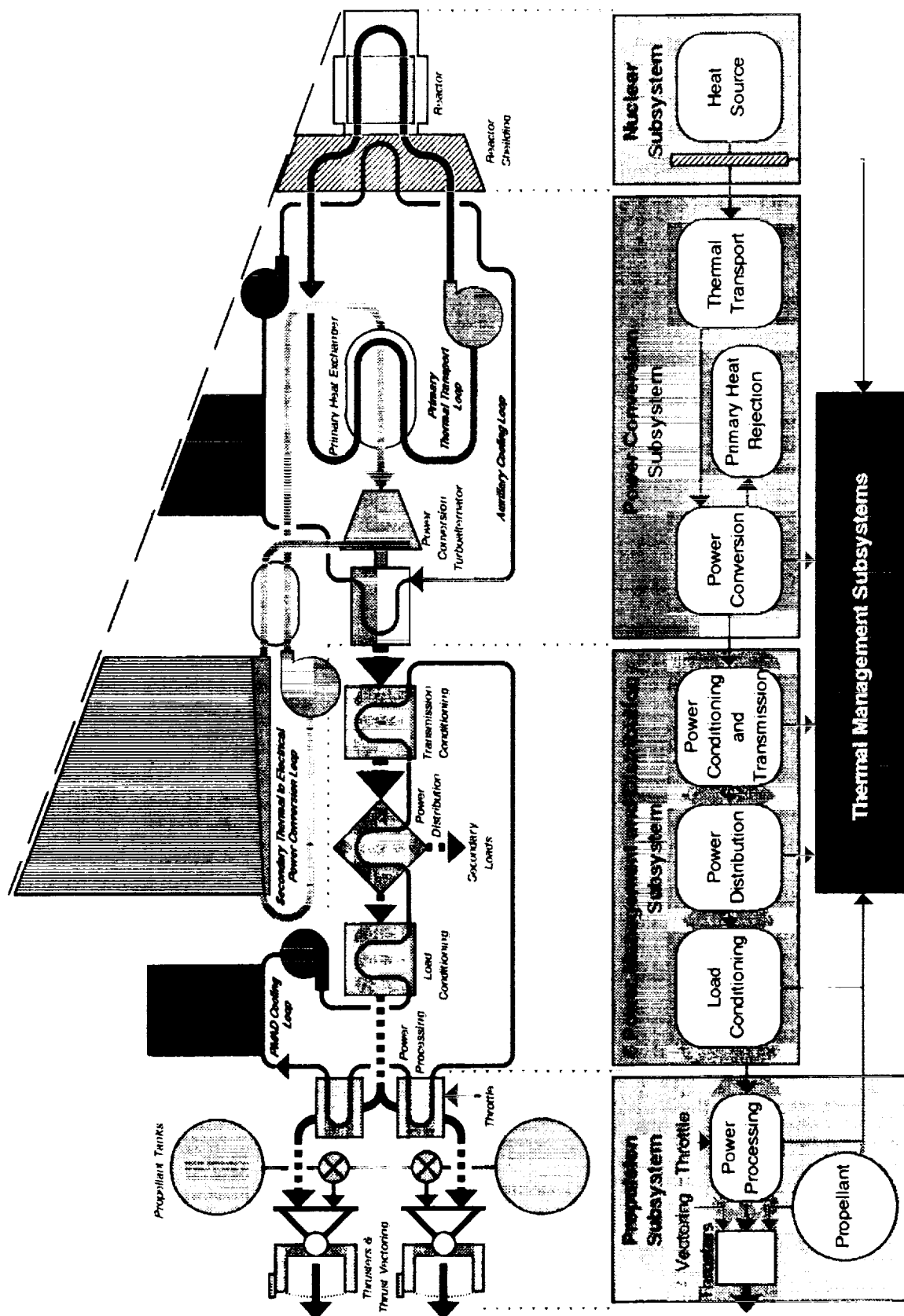
ACKNOWLEDGMENTS

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Nuclear Electric Propulsion System Schematic
Example High Power Dynamic System for Piloted Missions

Figure 1.

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Figure 2.
POTASSIUM-RANKINE POWER CONVERSION SYSTEM
SCHEMATIC

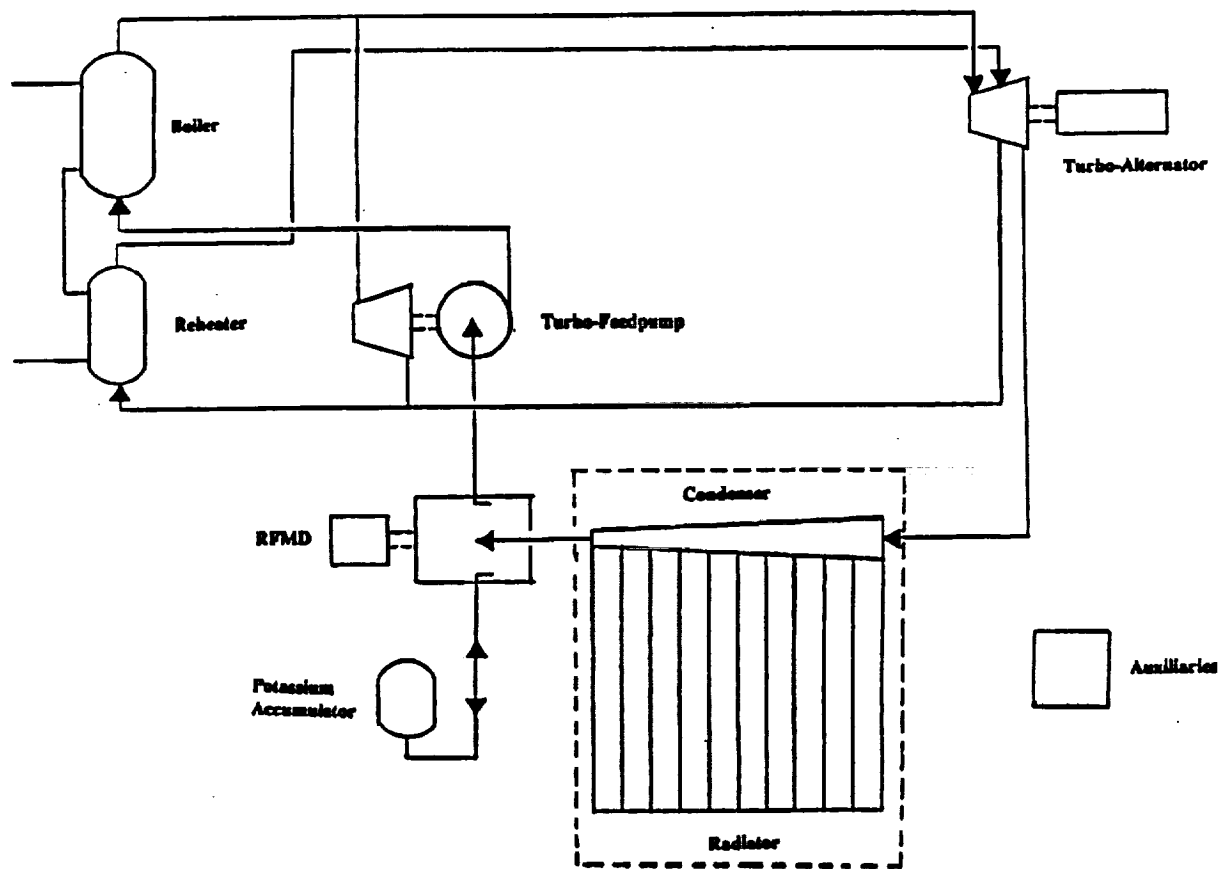
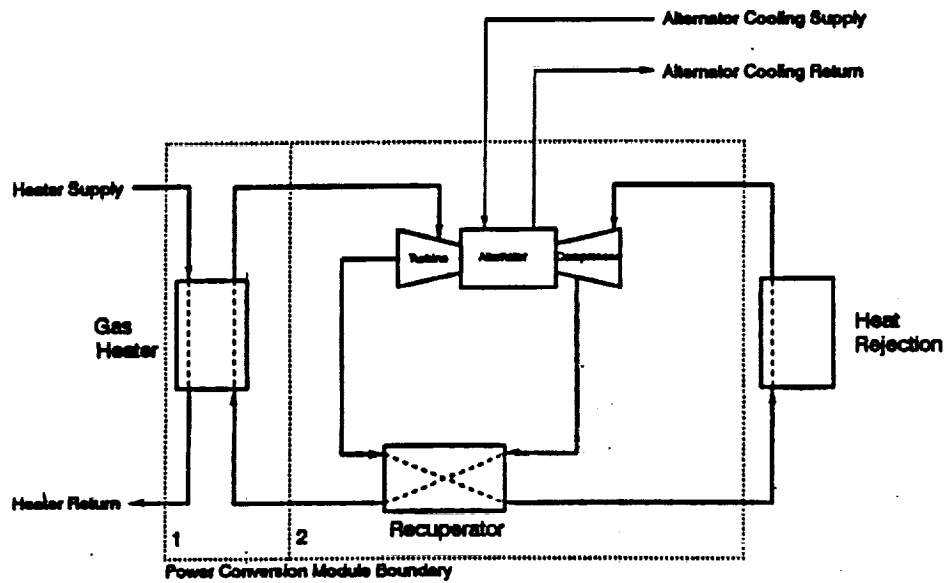


Figure 3.
Brayton
Power Conversion Module Flow Diagram



- 1. Full system module boundary
- 2. Gas reactor system option module boundary

Figure 4.
Power System Specific Mass vs. Compressor Inlet Temperature

